

Measurement of branching fractions of B^0 decays to $K_1(1270)^+\pi^-$ and $K_1(1400)^+\pi^-$

The *BABAR* Collaboration

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Abstract

We present a measurement of the branching fraction of neutral B meson decaying to final states containing a K_1 meson, i.e. $K_1(1270)$ and $K_1(1400)$, and a charged pion. The data, collected with the *BABAR* detector at the Stanford Linear Accelerator Center, represent 454 million $B\bar{B}$ pairs produced in e^+e^- annihilation. We measure the branching fraction $\mathcal{B}(B^0 \rightarrow K_1^+\pi^-) = (31.0 \pm 2.7 \pm 6.9) \times 10^{-6}$, where the first error quoted is statistical and the second is systematic. In the framework of the K -matrix formalism used to describe these decays, we also set limits on the ratio of the production constants for the $K_1(1270)^+$ and $K_1(1400)^+$ mesons in B^0 decays.

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1 INTRODUCTION

B meson decays to final states containing an axial-vector meson and a pseudoscalar meson have been recently studied both experimentally and theoretically. Branching fractions of the B mesons decays to final states containing an $a_1(1260)$ or b_1 meson associated with a pion or a kaon have been measured experimentally [1]. Theoretical predictions for the branching fractions of B decay modes to final states containing an axial-vector and a pseudoscalar meson have been calculated assuming a naive factorization hypothesis [2, 3] and QCD factorization [4]. Expected branching fractions of these B meson decay modes are of the order of 10^{-6} .

Recently the *BABAR* Collaboration has measured CP -violating asymmetries in $B^0 \rightarrow a_1(1260)^\pm \pi^\mp$ decays and determined the angle α_{eff} [5]. In the absence of penguin contributions in these decay modes, this angle would coincide with the angle α of the unitary triangle of the Cabibbo-Kobayashi-Maskawa quark-mixing matrix [6]. Theoretical bounds on $\Delta\alpha = \alpha - \alpha_{\text{eff}}$ in these decay modes based on $SU(3)$ flavor-symmetry have been derived in [7]. The rates of $B \rightarrow K_1(1270)\pi$ and $B \rightarrow K_1(1400)\pi$ decays are experimental inputs to the calculation of these bounds. For the $K_1(1400)^+ \pi^-$ decay mode ⁸ there exists a published experimental upper limit at 90% confidence level (CL) of 1.1×10^{-3} [8]. Preliminary results for the branching fractions of the $K_1(1270)^+ \pi^-$ and $K_1(1400)^+ \pi^-$ decay modes were obtained by the *BABAR* Collaboration on a sample of 384 million $B\bar{B}$ pairs [9]. In the following, we use K_1 to indicate both $K_1(1270)$ and $K_1(1400)$ mesons.

2 THE *BABAR* DETECTOR AND DATASET

The results presented here are based on a sample of $N_{B\bar{B}} = 454.3 \pm 5.0$ million $B\bar{B}$ pairs collected with the *BABAR* detector [10] at the PEP-II e^+e^- asymmetric-energy storage rings. The e^+e^- center-of-mass energy \sqrt{s} is equal to 10.58 GeV, corresponding to the $\Upsilon(4S)$ resonance.

Momenta of charged particles are measured in a tracking system consisting of a silicon vertex tracker with five double-sided layers and a 40-layer drift chamber, both within the 1.5 T magnetic field of a solenoid. Identification of charged hadrons is provided by measurements of the energy loss in the tracking devices and by a ring-imaging Cherenkov detector. For lepton identification, we use the energy deposit in a CsI(Tl) electromagnetic calorimeter and the pattern of hits in resistive plate chambers (partially upgraded to limited streamer tubes for a subset of the data used in this analysis) intervalled with the passive material comprising the solenoid magnetic flux return.

3 ANALYSIS METHOD

The $B^0 \rightarrow K_1^+ \pi^-$ candidates are identified from the $K_1^+ \rightarrow K^+ \pi^+ \pi^-$ final state, with reconstructed mass $m_{K\pi\pi}$ in the $[1.1, 1.8]$ GeV/ c^2 range. They are kinematically characterized by $m_{\text{ES}} = [(s/2 + \mathbf{p}_T \cdot \mathbf{p}_B)^2 / E_T^2 - \mathbf{p}_B^2]^{1/2}$ and $\Delta E = (E_T E_B - \mathbf{p}_T \cdot \mathbf{p}_B - s/2) / \sqrt{s}$, where (E_B, \mathbf{p}_B) is the four-momentum of the B candidate, and (E_T, \mathbf{p}_T) is the e^+e^- initial state four-momentum, both in the laboratory frame. We require $m_{\text{ES}} > 5.25$ GeV/ c^2 and $|\Delta E| < 0.15$ GeV.

To reject the dominant $e^+e^- \rightarrow$ quark-antiquark background, we use the thrust angle θ_T between the B -candidate thrust axis and that of the rest of the event, calculated in the center-of-mass (CM) frame, and a Fisher discriminant \mathcal{F} [11]. The discriminant combines the polar angles of the B -momentum vector and the B -candidate thrust axis with respect to the beam axis, and the zeroth

⁸Except as noted explicitly, we use a particle name to denote either member of a charge conjugate pair.

and second moments of the energy flow around the B -candidate thrust axis, calculated in the CM frame [11].

The resonant $K^+\pi^+\pi^-$ system can receive contributions from several strange resonances in the selected range for $m_{K\pi\pi}$, besides K_1 mesons, such as $K_1^*(1410)^+$ ($J^P = 1^-$), $K_1^*(1680)^+$ (1^-), and $K_2^*(1430)^+$ (2^+). Decays containing any of these resonances are characterized by different angular distributions. We define \mathcal{H} as the cosine of the angle between the direction of the primary pion from B decay and the normal to the plane defined by K_1 daughters in K_1 rest frame. We require $|\mathcal{H}| < 0.95$ to reduce background from $B^0 \rightarrow V^+\pi^-$ decay modes, where V^+ is a vector meson decaying to $K^+\pi^+\pi^-$.

Background from B decays to final states with charm is suppressed by rejecting a signal candidate if it has at least one track in common with a background B candidate, reconstructed in any of the $B^0 \rightarrow D^-\pi^+$, $B^0 \rightarrow D^{*-}\pi^+$, and $B^+ \rightarrow \bar{D}^0\pi^+$ background decay channels, with D meson mass within $0.07 \text{ GeV}/c^2$ of the nominal value (if more than one such background candidates are reconstructed per event per background channel, the one with the highest B vertex fit χ^2 probability is chosen). To suppress background from B decays to final states with charmonium we calculate the invariant mass of the neutral $\pi\pi$ combination of the primary pion from B decay with the opposite charge pion from K_1 decay, and require that it is not consistent with any of the $c\bar{c}$ mesons J/ψ , $\psi(2S)$, η_c , $\eta_c(2S)$, $\chi_{c0}(1P)$, and $\chi_{c1}(1P)$. We also make particle identification requirements to identify pions and kaons, and veto muons, electrons and protons.

The average number of candidates found per selected event in the data sample is 1.20. In case of events with multiple candidates, we select the candidate with the highest B vertex fit χ^2 probability. We classify the events according to the invariant masses of the $K^+\pi^-$ and $\pi^+\pi^-$ systems in the $K_1^+ \rightarrow K^+\pi^+\pi^-$ final state: events which satisfy the requirement $0.846 < m_{K\pi} < 0.946 \text{ GeV}/c^2$ belong to class 1 (" K^* region"); events not included in class 1 for which $0.500 < m_{\pi\pi} < 0.800 \text{ GeV}/c^2$ belong to class 2 (" ρ region"); all other events are rejected.

A two-resonances, six channels K -matrix model [12] is used to describe the resonant $K\pi\pi$ system for the signal [13]. The notation is consistent with that used in [13]. The labels a and b in the following paragraphs refer to $K_1(1400)$ and $K_1(1270)$, respectively. The production amplitude for channel $i = \{(K^*\pi)_{S\text{-wave}}, (K^*\pi)_{D\text{-wave}}, \rho K, K_0^*\pi, f_0(1370) K, \omega K\}$ is given by

$$F_i = e^{i\delta_i} \sum_j (1 - i\mathbf{K}\boldsymbol{\rho})_{ij}^{-1} \mathbf{P}_j, \quad (1)$$

where

$$K_{ij} = \frac{f_{ai}f_{aj}}{M_a - M} + \frac{f_{bi}f_{bj}}{M_b - M}, \quad (2)$$

δ_i are offset phases ($\delta_{(K^*\pi)_S} \equiv 0$), and \mathbf{P} is the production vector

$$P_i = \frac{f_{pa}f_{ai}}{M_a - M} + \frac{f_{pb}f_{bi}}{M_b - M}. \quad (3)$$

The decay constants f_{ai} , f_{bi} and the K -matrix poles M_a and M_b are real. The elements of the diagonal phase space matrix $\boldsymbol{\rho}$ for the process $K_1 \rightarrow 3 + 4$, $3 \rightarrow 5 + 6$, where 4, 5 and 6 are long-lived pseudoscalar particles and 3 is a resonance, have been approximated with the form

$$\rho_i(M) = \frac{\sqrt{8}}{M} \left[\frac{m^*m_4}{m^* + m_4} (M - m^* - m_4 + i\Delta) \right]^{1/2}, \quad (4)$$

where M is the mass of K_1 , m_4 is the mass of 4, m^* is the mean mass of 3 and Δ is the half width of 3 [14]. The parameters of \mathbf{K} and the offset phases δ_i are obtained from a fit to the intensity and the relative phases of the $K\pi\pi$ channels, which were extracted by the ACCMOR Collaboration in a partial wave analysis of the data on the reaction $K^-p \rightarrow K^-\pi^+\pi^-p$ accumulated by the WA3 experiment [13]. For the fit to WA3 data we add a background term to the production vector [15]. The decay constants for the ωK channel are fixed according to the quark model [13].

We express the complex production constants f_{pa} and f_{pb} in terms of the production parameters $\zeta = (\theta, \phi)$: $f_{pa} \equiv \cos \theta$, $f_{pb} \equiv \sin \theta e^{i\phi}$, where $\theta \in [0, \pi/2]$, and $\phi \in [0, 2\pi]$. In this parameterization, $\tan \theta$ represents the magnitude of the production constant for the $K_1(1270)$ meson relative to that for the $K_1(1400)$ meson, while ϕ is the relative phase.

Signal MC samples are generated by weighting the $(K^+\pi^+\pi^-)\pi^-$ population according to the amplitude $\sum_{i \neq \omega K} \langle K^+\pi^+\pi^- | i \rangle F_i$, where the term $\langle K^+\pi^+\pi^- | i \rangle$ consists of a factor describing the angular distribution of the $(K^+\pi^+\pi^-)$ system resulting from K_1 decay, an amplitude for the resonant $\pi^+\pi^-$ and $K^+\pi^-$ systems, and isospin factors, and is calculated using the formalism described in [16]. The branching fraction for $K_1 \rightarrow \omega K$ is accounted for as a correction to the total selection efficiency.

We use an unbinned, extended maximum-likelihood (ML) fit to extract the event yields $n_{s,r}$ and the parameters of the probability density function (PDF) $\mathcal{P}_{s,r}$. The subscript $r = \{1, 2\}$ corresponds to one of the event classes defined above. The index s represents six event categories used in our data model:

- the signal $B^0 \rightarrow K_1^+\pi^-$ ($s = 1$),
- possible backgrounds from $B^0 \rightarrow a_1(1260)^\pm\pi^\mp \rightarrow (\pi^\pm\pi^+\pi^-)\pi^\mp$ ($s = 2$),
- $B^0 \rightarrow D^-\pi^+ \rightarrow (K^+\pi^-\pi^-)\pi^+$ ($s = 3$),
- $B^0 \rightarrow K^*(1410)^+\pi^-$ ($s = 4$),
- $B^0 \rightarrow K^{*0}\pi^+\pi^- + \rho^0 K^+\pi^-$ ($s = 5$),
- combinatorial background ($s = 6$).

We perform a likelihood scan with respect to the parameters ζ , with 21×21 points. At each point, a simultaneous fit to the two event classes is performed.

The signal and background PDFs are the products of the PDFs for independent variables. The signal PDFs for ΔE , m_{ES} , and \mathcal{F} are parameterized as the sum of Gaussian functions for the core of the distributions plus empirical functions accounting for the tails. The dependence on ζ of the selection efficiencies and the signal PDF for $m_{K\pi\pi}$ are parameterized by means of templates modeled upon signal MC samples. Resonance production occurs in the non-signal B background and is taken into account in the PDFs. For the combinatorial background, we use polynomials, except for m_{ES} and \mathcal{F} distributions which are parameterized by an empirical phase-space function [18] and by Gaussian functions, respectively. The combinatorial background PDF is found to describe well both the dominant quark-antiquark background and the background from random combinations of B tracks. For all components, PDFs for \mathcal{H} are parameterized with polynomials.

The likelihood \mathcal{L}_e for each candidate e belonging to class r is defined as $\mathcal{L}_e = \sum_s n_{s,r} \mathcal{P}_{s,r}(\mathbf{x}_e; \zeta, \xi)$, where the PDFs are formed using the set of observables $\mathbf{x}_e = \{\Delta E, m_{\text{ES}}, \mathcal{F}, m_{K\pi\pi}, \mathcal{H}\}$ and the dependence on production parameters ζ is relevant only for the signal PDF. ξ represents all other PDF parameters. In the definition of \mathcal{L}_e the yields of the signal category for the two classes

are expressed as a function of the signal branching fraction \mathcal{B} as $n_{1,1} = \mathcal{B} \times N_{B\bar{B}} \times \epsilon_1(\zeta)$ and $n_{1,2} = \mathcal{B} \times N_{B\bar{B}} \times \epsilon_2(\zeta)$, where the total selection efficiency, $\epsilon_r(\zeta)$, includes the daughter branching fractions and the reconstruction efficiency obtained from MC simulation.

The signal branching fraction is a free parameter in the fit. The yields for event categories $s = 2$ and 3 are fixed to the values estimated from MC. The yields for the other background components are determined from the fit. The PDF parameters for combinatorial background are left free to vary in the fit while those for the other event categories are fixed to the values extracted from Monte Carlo (MC) simulation [17] and calibration $B^0 \rightarrow D^-\pi^+$ decays.

4 SYSTEMATIC STUDIES

The main sources of systematic uncertainties are summarized in Table 1. We repeat the fit by varying all the parameters in ξ which were not left floating in the fit within their uncertainties, and obtain the associated systematic uncertainties. The signal PDF model excludes the fake combinations originating from mis-reconstructed signal events. The biases due to the presence of fake combinations, or other imperfections in the signal PDF model are estimated with MC simulation. The finite resolution of the likelihood scan is also a source of bias. A systematic error is evaluated by varying the $K_1(1270)$ and $K_1(1400)$ mass poles in the signal model, the parameterization of the intermediate resonances in K_1 decay, and the offset phases δ_i . Additional systematic uncertainty originates from potential peaking $B\bar{B}$ background, including $B^0 \rightarrow K_2^*(1430)^+\pi^-$ and $B^0 \rightarrow K_1^*(1680)^+\pi^-$, and is evaluated by introducing the corresponding components in the definition of the likelihood and repeating the fit with their yields fixed to values estimated from the available experimental information [20]. We assign a systematic uncertainty due to yield variation in the $B^0 \rightarrow a_1(1260)^\pm\pi^\mp$ and $B^0 \rightarrow D_{K^+\pi^-\pi^-}^-\pi^+$ event categories. The above systematic uncertainties do not scale with event yield and are included in the calculation of the significance of the result.

We estimate the systematic uncertainty due to the interference between the $B^0 \rightarrow K_1^+\pi^-$ and the $B^0 \rightarrow K^{*0}\pi^+\pi^- + \rho^0 K^+\pi^-$ decays using simulated samples in which the decay amplitudes are generated according to the results of this measurement. The overall phases and relative contribution for $K^{*0}\pi^+\pi^-$ and $\rho^0 K^+\pi^-$ interfering states are assumed to be constant across the phase space and varied between zero and a maximum value using uniform prior distributions. We calculate the systematic uncertainty from the RMS variation of the average signal branching fraction and parameters. In the calculation of significance, this effect is assumed to scale with the square root of the signal branching fraction. The systematic uncertainties in efficiencies are dominated by those in track finding and particle identification. Other systematic effects arise from event-selection criteria, such as track multiplicity and thrust angle, and the number of B mesons.

5 RESULTS

Figure 1 shows the likelihood scan and the values of \mathcal{B}_{sg} which minimize $-\ln\mathcal{L}$ as a function of θ and ϕ . The absolute minimum occurs at $\theta = 0.785$ and $\phi = 0.942$, and the signal branching fraction corresponding to that point of the scan is $\mathcal{B}(B^0 \rightarrow K_1^+\pi^-) = (31.0 \pm 2.7) \times 10^{-6}$. By interpolation between neighbouring points of the likelihood scan we extract $\theta = 0.81 \pm 0.06$ and $\phi = 1.11 \pm 0.28$. The quoted errors on the branching fraction and production parameters ζ are only statistical and correspond to a 0.5 increase in $-\ln\mathcal{L}$. A second, local minimum is located at $\theta = 0.785$ and $\phi = 3.454$, and is associated to a 1.0 increase in $-\ln\mathcal{L}$.

Table 1: Estimates of systematic errors. For the branching fraction, some of these errors are additive (A) and given in units of 10^{-6} , others are multiplicative (M) and given in % . Contributions are combined in quadrature.

Quantity	\mathcal{B}	θ	ϕ
PDF parameters (A)	1.0	0.01	0.04
MC/data correction (A)	1.2	0.05	0.27
ML Fit bias (A)	0.6	0.03	0.02
Scan (A)	1.3	0.04	0.16
K_1 mass poles (A)	2.2	0.01	0.36
K_1 offset phases (A)	0.2	0.01	0.02
K_1 intermediate resonances (A)	0.5	0.00	0.06
Peaking $B\bar{B}$ bkg (A)	0.8	0.02	0.27
Fixed background yields (A)	0.8	0.04	0.08
Interference (A)	5.9	0.25	0.52
MC statistics (M)	1.0	—	—
Particle ID (M)	2.9	—	—
Track finding (M)	1.0	—	—
$\cos \theta_T$ (M)	1.0	—	—
Track multip. (M)	1.0	—	—
Number $B\bar{B}$ (M)	1.1	—	—
Total (A)	6.9	0.26	0.76

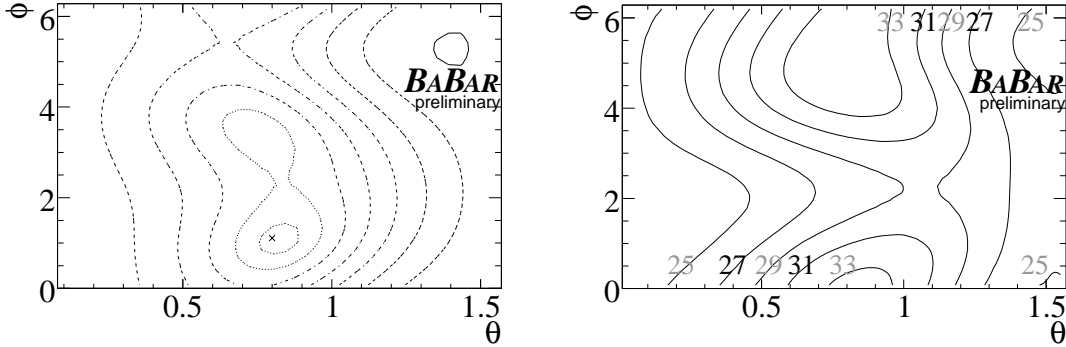


Figure 1: Left: contour plot of $-\ln \mathcal{L}$ (no systematic effects included) in the θ, ϕ plane; each line corresponds to a $n^2/2$ increase in $-\ln \mathcal{L}$, with $n = \{1, 2, \dots\}$, with respect to the minimum (indicated by a cross). Right: fitted value of \mathcal{B}_{sg} , in units of 10^{-6} as a function of θ and ϕ .

A conservative estimate of significance is calculated from a likelihood ratio test $\Delta(-2\ln \mathcal{L})$, assuming a χ^2 distribution with $N = 3$ degrees of freedom and minimizing the significance with respect to the production parameters (θ, ϕ) . Here $\Delta(-2\ln \mathcal{L})$ is the difference between the value of $-2\ln \mathcal{L}$ for zero signal and the value at its minimum for given values of ζ (\mathcal{L} represents the convolution of the likelihood with a Gaussian function representing additive systematic uncertainties on the branching fraction). We observe a non zero $B^0 \rightarrow K_1^+ \pi^-$ branching fraction with significance

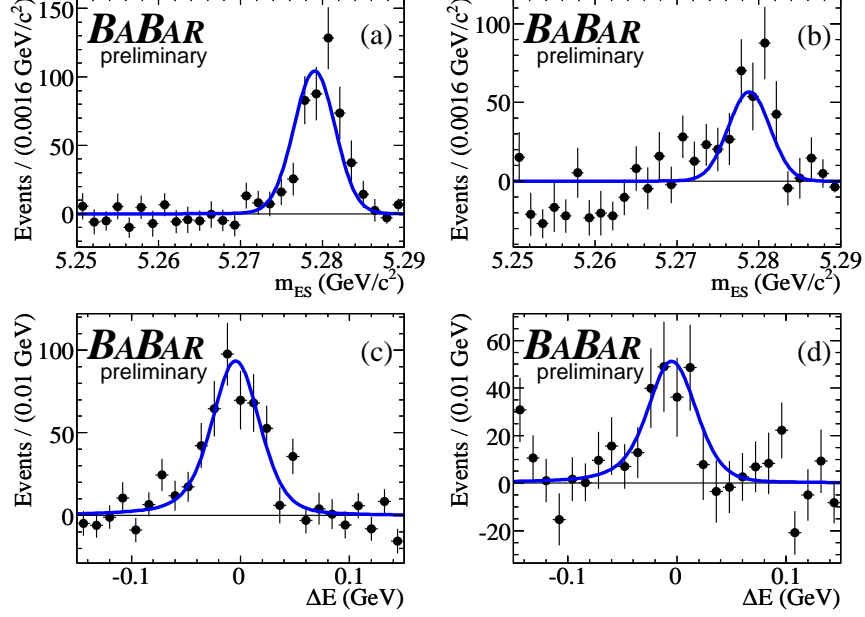


Figure 2: sPlot projections onto a) m_{ES} (class 1), b) m_{ES} (class 2), c) ΔE (class 1), d) ΔE (class 2) in the $K_1\pi$ decay. Points represent on-resonance data, solid line is the signal fit function.

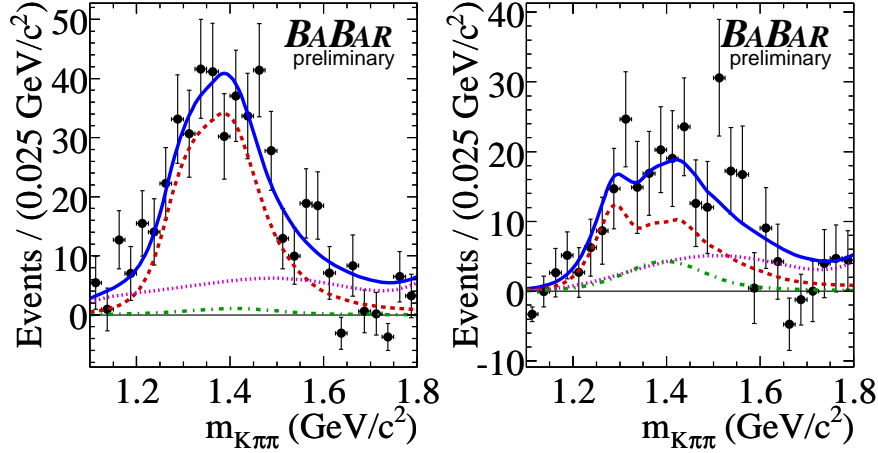


Figure 3: sPlot projection onto $m_{K\pi\pi}$ for class 1 (left) and class 2 events (right). Points represent on-resonance data, solid line is the sum of the fit functions of the decay modes $K_1(1270)\pi + K_1(1400)\pi$ (dashed), $K^*(1410)\pi$ (dash-dotted), and $K^*(892)\pi\pi$ (dotted). Here the points are obtained without using any information about resonances in the fit, *i.e.* we use only m_{ES} , ΔE , and \mathcal{F} variables, while for the normalization of the curves we use the signal yields obtained from the nominal fit.

greater than 5.1σ .

Figure 2 shows the distributions of ΔE and m_{ES} for the signal events, obtained by the event-weighting technique (sPlot) described in [19]. For each event, a weight to be signal or background

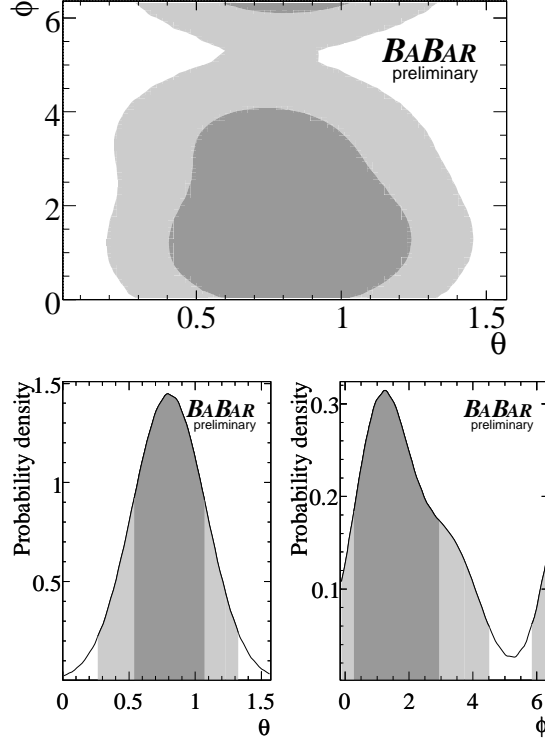


Figure 4: 68 % (dark shaded zone) and 95 % (light shaded zone) probability regions for θ and ϕ (top), θ (bottom-left) and ϕ (bottom-right).

is derived according to the results of the fit to all variables and the probability distributions in the restricted set of variables, in which the projection variable is omitted. Using these weights, the data is then plotted in the projection variable. We show in Figure 3 the projection onto $m_{K\pi\pi}$.

The experimental two-dimensional likelihood \mathcal{L} for θ and ϕ is convoluted with a two-dimensional Gaussian that accounts for the systematic uncertainties. In Figure 4 we show the distributions we obtain for θ , ϕ and θ vs. ϕ (the 68% and 95% probability regions are shown in dark and light shading respectively, and are defined as the regions which satisfy $\mathcal{L}(r) > \mathcal{L}_{min}$ and $\int_{\mathcal{L}(r) > \mathcal{L}_{min}} \mathcal{L}(r) dr = 68\%$ (95%), where r is the projected set of variables). The condition $\mathcal{L}(r) > \mathcal{L}_{II}$, where \mathcal{L}_{II} is the value of the likelihood evaluated at the position of the second, local minimum in Figure 1, defines a 48% probability region, with systematic uncertainties included, on the θ vs. ϕ plane.

6 CONCLUSIONS

We measure the branching fraction

$$\mathcal{B}(B^0 \rightarrow K_1^+ \pi^-) = (31.0 \pm 2.7 \pm 6.9) \times 10^{-6},$$

with significance greater than 5.1σ . The first error quoted is statistical and the second systematic. The value of the branching fraction measured in this analysis is consistent with preliminary results obtained by *BABAR* Collaboration [9], and is to be compared with the naive factorization [2, 3] and QCD factorization [4] estimates, of order 10^{-6} .

For the production parameters we obtain

$$\begin{aligned} 0.25 &< \theta < 1.32 \\ -0.51 &< \phi < 4.51 \end{aligned}$$

at 95% probability. This analysis represents the first attempt to measure the relative phase between the production amplitudes of $K_1(1270)$ and $K_1(1400)$ mesons in B decays.

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